Superconductivity: Exotic Commonalities in Phase and Mode

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Recent muon and neutron experiments on the new FeAs-based superconductors revealed phase diagrams characterized by first-order evolution from antiferromagnetic to superconducting states, and an inelastic magnetic resonance mode whose energy scales as $\sim 4k_BT_c$. These features exhibit striking commonalities with cuprate, backyball, organic, and heavy-fermion superconductors as well as superfluid ^{4}He.

For every new superconducting system, determination of the phase diagram is both a starting point and a major goal of experimental studies. Muon spin relaxation (μSR) and neutron scattering are two strong particle probes for this purpose. In the present issue, two muon groups report their findings in RE(O,F)FeAs with RE=La [1] and Sm [2]. Together with the earlier neutron study on RE=Ce [3], these represent first sets of the phase diagrams of the "1111" FeAs superconductor family first discovered in February of 2008 [4]. As seen in Fig. 1(a), the three results exhibit differences in details, but they indicate that the superconducting (SC) state takes over the antiferromagnetic (AF) state, with abrupt disappearance of the AF state for RE=La, and phase-separated coexistence of AF and SC regions in RE=Sm.

As compared to neutron scattering, μSR has better sensitivities to static magnetic order with random or small moments, and can clearly determine the volume fraction of magnetically ordered regions near the phase boundaries [5]. These advantages are fully employed in the studies of the La and Sm systems. A more recent muon study in the RE=Ce system near the SC-AF boundary [6] indicates that the RE=Ce system also shows evolution similar to that of RE=La. All together, we observe behavior significantly different from the standard picture of second-order evolution from the AF to SC states associated with a quantum critical point (QCP). The abrupt disappearance of the magnetic phase and phase separation of the AF and SC states are both characteristic of first-order quantum evolution at $T \to 0$.

As shown in Fig. 1(b)-(e), these features are found in various other superconductors, including the "122" FeAs system (Ba,K)Fe_2As_2 by neutrons [7] (1(b)) and muons [8], the YBCO cuprate system (1(c)) by muons [9], alkali-doped A_3C_{60} (1(d)) by muons and EPR [10], organic BEDT by NMR [11], $CeRhIn_5$ (1(e)) by transport and calorimetry [12], and $CeCu_2Si_2$ by muons [13]. The boundary of the SC and static spin stripe states in the 214 cuprate systems is associated with phase separation [14]. The phase diagram for superfluid ^{4}He also looks quite similar (Fig. 1(f)).

Spectacular commonality also exists with the energy scale of neutron inelastic excitations observed in the SC (or superfluid) state. Recent observation of the magnetic resonance mode in (Ba,K)Fe_2As_2 [15] (Fig. 2(a)) follows earlier results in the cuprates [16], $CeCoIn_5$ [17], and $CeCu_2Si_2$ [18]. The magnetic resonance mode appears with the same symmetry as the AF correlations (shown by the blue closed circle in Fig. 2(a)), as short-range and dynamic spin correlations related to the AF state. In this sense, the resonance mode may be analogous to rotons in superfluid ^{4}He (Fig. 2(b) [19]), which are inelastic soft phonon modes associated with the imminent HCP solid state whose Bragg points are shown by the blue closed circles in Fig. 2(b).

Indeed, when compared in a plot of T_c versus mode energy $\hbar\omega$ in Fig. 2(c) [6, 19, 20], all these excitations exhibit nearly identical linear slopes of $\hbar\omega \sim 4k_BT_c$. The resonance mode in cuprates appears with an "hourglass"-shaped dispersion [21]. If we use the energy of the lower end of populated states in this dispersion curve, often referred to as the spin-gap energy and shown by closed squares in Fig. 2(c), the slope agrees well with those of all the other systems. The energy of the inelastic A_{1g} Raman mode in cuprates [22] also follows this correlation, hinting that not only a spin phenomenon but also a charge phenomenon might join this argument [20].

Figure 2(c) suggests that the transition temperature T_c of the SC (or superfluid) state may be determined by the energy of such "soft-mode" dynamic excitations related to the adjacent antiferromagnetic (or solid) state, whose energy represents the "closeness to the competing AF (or HCP) state". The first-order-like evolution, seen in Fig. 1, actually helps existence of dynamic modes which are often very sharp in both momentum and energy space. In systems exhibiting second order transitions, at points somewhat away from the QCP, one would expect much broader and diffusive inelastic responses. Although the details need to be clarified by further studies, these exotic commonalities suggest the importance of strong coupling and collective modes, and promote researchers to think beyond textbook cases of second order transitions, quantum critical points, weak coupling, and single (quasi) particle descriptions.

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[1] H. Luetkens, H.-H. Klauss, M. Kraken, F.J. Litterst, T. Dellmann, R. Klingeler, C. Hess, R. Khasanov, A. Amato, C. Baines, M. Kosmala, O.J. Schumann, M. Braden, J. Hamann-Borrero, N. Leps, A. Kondrat, G. Behr, J. Werner, B. Buechner, *Electronic phase diagram of the* $LaO_{1-x}F_xFeAs$ *superconductor* , Nature Materials, this issue.

[2] A.J. Drew, Ch. Niedermayer, P.J. Baker, F.L. Pratt, S.J. Blundell, T. Lancaster, R.H. Liu, G. Wu, X.H. Chen, I. Watanabe, V.K. Malik, A. Dubroka, M. Roessle, K.W. Kim, C. Baines, C. Bernhard, *Coexistence of static magnetism and superconductivity in* $SmFeAsO_{1-x}F_x$ *as revealed by muon spin rotation*, Nature Materials, this issue.

[3] J. Zhao, Q. Huang, C. de la Cruz, S. Li, J.W. Lynn, Y. Chen, M.A. Green, G.F. Chen, G. Li, Z. Li, J.L. Luo, N.L. Wang, P.C. Dai, *Structural and magnetic phase diagram of* $CeFeAsO_{1-x}F_x$ *and its relationship to high-temperature superconductivity*, Nature Mateirals **7** (2008) 953-959.

[4] Y. Kamihara, T. Watanabe, M. Hirano, H. Hosono, *Iron-based layered superconductor* $La[O_{1-x}F_x]FeAs$ *(x=0.05-0.12) with* T_c*=26 K*, J. Am. Chem. Soc. **130** (2008) 3296 - 3297.

[5] Y.J. Uemura, T. Goko, I.M. Gat-Malureanu, J.P. Carlo, P.L. Russo, A.T. Savici, A. Aczel, G.J. MacDougall, J.A. Rodriguez, G.M. Luke, S.R. Dunsiger, A. McCollam, J. Arai, Ch. Pfleiderer, P. Böni, K. Yoshimura, E. Baggio-Saitovitch, M.B. Fontes, J. Larrea J., Y.V. Sushko, and J. Sereni, *Phase separation and suppression of critical dynamics at quantum phase transitions of MnSi and* $(Sr_{1-x}Ca_x)RuO_3$, Nature Physics **3** (2007) 29-35.

[6] Y.J. Uemura, *Energy-scale phenomenology and pairing via resonant spin-charge motion in FeAs, CuO, heavy-fermion and other exotic superconductors*, Cond-mat arXiv:0811.1546 (2008). Plenary talk presented at the International Conference on Strongly Correlated Electron Systems (SCES2008), Buzios, Brazil, August, 2008. To be published in the Proceedings, Physica **B** (2009) in press.

[7] H. Chen, Y. Ren, Y. Qiu, W. Bao, R.H. Liu, G. Wu, T. Wu, Y.L. Xie, X.F. Wang, Q. Huang, X.H. Chen, *Coexistence of the spin-density-wave and superconductivity in the* $(Ba,K)Fe_2As_2$, Europhys. Lett. **85** (2009) 17006.

[8] T. Goko, A.A. Aczel, E. Baggio-Saitovitch, S.L. Bud'ko, P.C. Canfield, J.P. Carlo, G.F. Chen, P.C. Dai, A.C. Hamann, W.Z. Hu, H. Kageyama, G.M. Luke, J.L. Luo, B. Nachumi, N. Ni, D. Reznik, D.R. Sanchez-Candela, A.T. Savici, K.J. Sikes, N.L. Wang, C.R. Wiebe, T.J. Williams, T. Yamamoto, W. Yu, Y.J. Uemura, *Superconductivity coexisting with phase-separated static magnetic order in* $(Ba,K)Fe_2As_2$, $(Sr,Na)Fe_2As_2$ *and* $CaFe_2As_2$, Cond-mat arXiv:0808.1425.

[9] S. Sanna, G. Allodi, G. Concas, A.D. Hillier, and R. De Renzi, *Nanoscopic Coexistence of Magnetism and Superconductivity in* $YBa_2Cu_3O_{6+x}$ *Detected by Muon Spin Rotation*, Phys. Rev. Lett. **93** (2004) 207001.

[10] J. Arvanitidis, K. Papagelis, Y. Takabayashi, T. Takenobu, Y. Iwasa, M.J. Rosseinsky and K. Prassides, *Magnetic ordering in the ammoniated alkali fullerides* $(NH_3)K_{3-x}Rb_xC_{60}$ *(x = 2, 3)*, J. Phys.: Condens. Matter **19** (2007) 386235 (13pp).

[11] F. Kagawa, K. Miyagawa, K. Kanoda, *Unconventional critical behaviour in a quasi-two-dimensional organic conductor*, Nature **436** (2005) 534-537.

[12] G. Knebel, D. Aoki, D. Braithwaite, B. Salce, and J. Flouquet, *Coexistence of antiferromagnetism and superconductivity in* $CeRhIn_5$ *under high pressure and magnetic field*, Phys. Rev. **B74** (2006) 020501.

[13] G.M. Luke, A. Keren, K. Kojima, L.P. Le, B.J. Sternlieb, W.D. Wu, Y.J. Uemura, Y. Onuki, and T. Komatsubara, *Competition between Magnetic Order and Superconductivity in* $CeCu_{2.2}Si_2$, Phys. Rev. Lett. **73** (1994) 1853-1856.

[14] A.T. Savici, Y. Fudamoto, I.M. Gat, T. Ito, M.I. Larkin, Y.J. Uemura, G.M. Luke, K.M. Kojima, Y.S. Lee, M.A. Kastner, R.J. Birgeneau, K. Yamada, *Muon spin relaxation studies of incommensurate magnetism and superconductivity in stage-4* $La_2CuO_{4.11}$ *and* $La_{1.88}Sr_{0.12}CuO_4$, Phys. Rev. **B66**, 014524 (2002); K.M. Kojima, S. Uchida, Y. Fudamoto, I.M. Gat, M.I. Larkin, Y.J. Uemura, G.M. Luke, *Superfluid density and volume fraction of static magnetism in stripe-stabilized* $La_{1.85-y}Cu_ySr_{0.15}CuO_4$, Physica **B 326**, 316-320 (2003).

[15] A.D. Christianson, E.A. Goremychkin, R. Osborn, S. Rosenkranz, M.D. Lumsden1, C.D. Malliakas, I.S. Todorov, H. Claus, D.Y. Chung, M.G. Kanatzidis, R.I. Bewley and T. Guidi, *Unconventional superconductivity in* $Ba_{0.6}K_{0.4}Fe_2As_2$ *from inelastic neutron scattering*, Nature **456** (2008) 930-932.

[16] P. Bourges, B. Keimer, S. Pailhes, L.P. Regnault, Y. Sidis, C. Ulrich, *The resonant magnetic mode: A common feature of high-*T_c *superconductors*, Physica **C424** (2005) 45-49.

[17] C. Stock, C. Broholm, J. Hudis, H.J. Kang, and C. Petrovic, *Spin Resonance in the d-Wave Superconductor* $CeCoIn_5$, Phys. Rev. Lett. **100** (2008) 087001.

[18] O. Stockert, J. Arndt, A. Schneidewind, H. Schnelder, H.S. Jeevan, C. Geibel, F. Steglich, M. Loewenhaupt, *Magnetism and superconductivity in the heavy-fermion compound* $CeCu_2Si_2$ *studied by neutron scattering*, Physica **B403** (2008) 973-976.

[19] D.G. Henshaw and A.D.B. Woods, *Modes of Atomic Motions in Liquid Helium by Inelastic Scattering of Neutrons*, Phys. Rev. **121** (1961) 1266; O.W. Dietrich, E.H. Graf, C.H. Huang, L. Passell, *Neutron scattering by rotons in liquid helium*, Phys. Rev. **A5** (1972) 1377.

[20] Y.J. Uemura, *Twin spin/charge roton mode and superfluid density: Primary determining factors of* T_c *in high-*T_c *superconductors observed by neutron, ARPES, and MuSR*, Physica **B374-375** (2006) 1-8.

[21] N.B. Christensen, D.F. McMorrow, H.M. Rønnow, B. Lake, S. Hayden, G. Aeppli, T.G. Perring, M. Mangkorntong, M. Nohara, H. Takagi, *Universal dispersive excitations in the high-temperature superconductors*, Phys. Rev. Lett. **93** (2004) 147002.

[22] Y. Gallais, A. Sacuto, P. Bourges, Y. Sidis, A. Forget and D. Colson, *Evidence for Two Distinct Energy Scales in the Raman Spectra of* $YBa_2(Cu_{1-x}Ni_x)_3O_{6.95}$, Phys. Rev. Lett. **88** (2002) 177401.

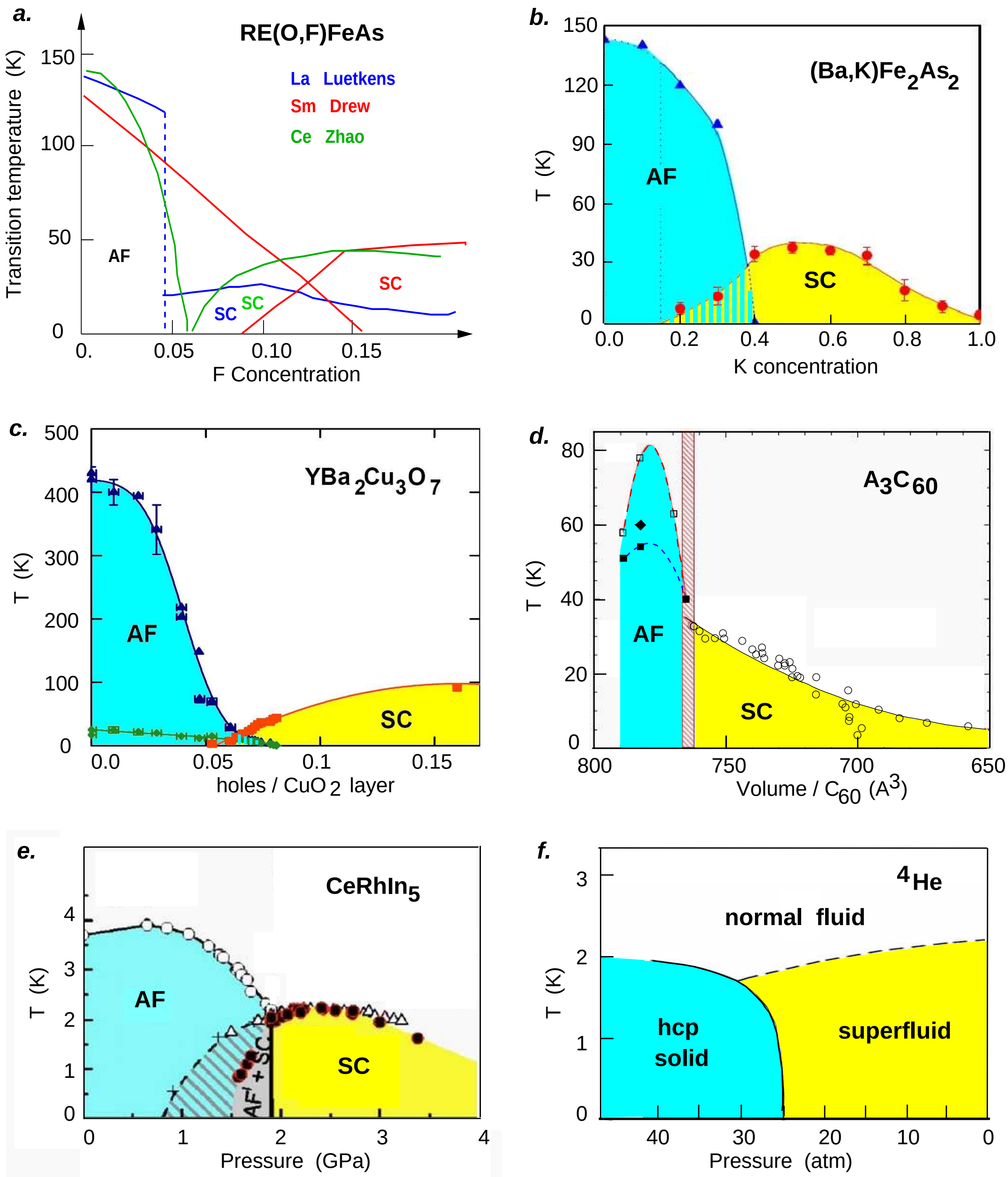

FIG. 1: (color) Electronic phase diagram, as functions of composition, pressure, and/or unit-cell volume in (a) RE(O,F)FeAs (RE = La, Sm, Ce)[1, 2, 3], (b) (Ba,K)Fe_2As_2 [7], (c) $YBa_2Cu_3O_{7-\delta}$ [9], (d) A_3C_{60} (A = K, Cs, Rb) [10], and (e) $CeRhIn_5$ [12] ($CeCoIn_5$ at ambient pressure corresponds to $CeRhIn_5$ at $p \sim 2.4$ GPa). Figure 1(f) shows the phase diagram of superfluid ^{4}He. All these systems exhibit abrupt disappearance of the antiferromagnetic (AF) or HCP solid phase or coexistence of the AF and the superconducting (SC) phases near the phase boundary.

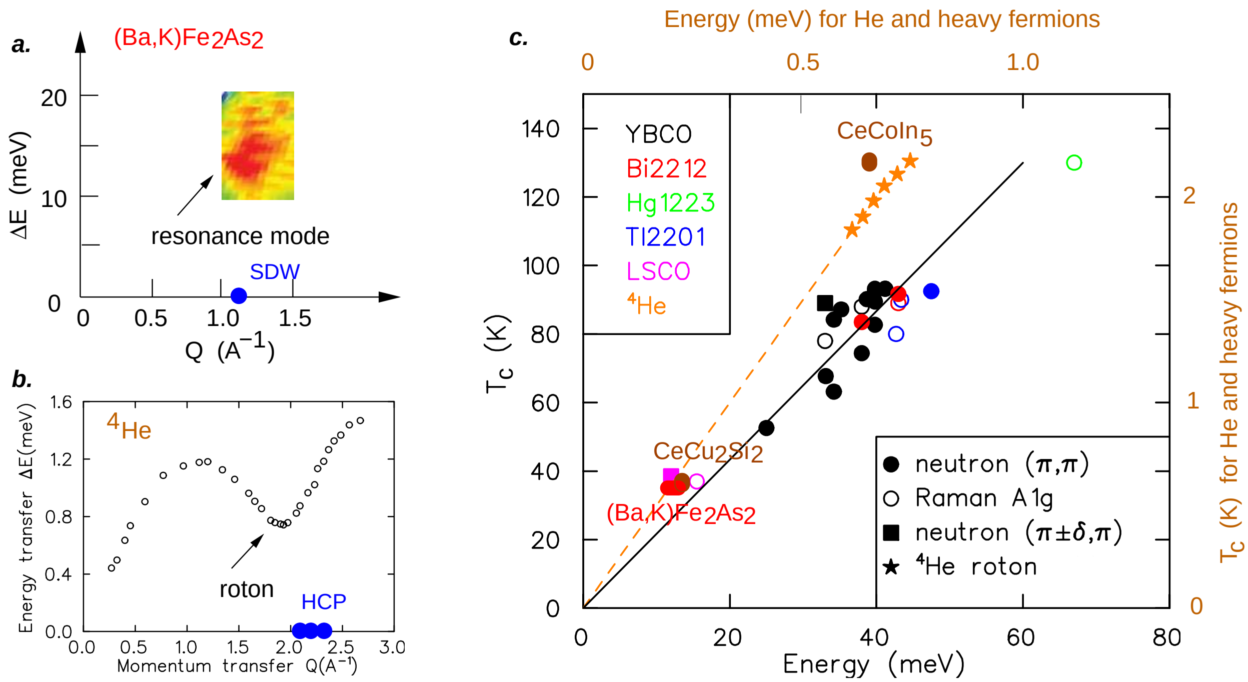

FIG. 2: (color) (a) Schematic view of the magnetic resonance mode in (Ba,K)Fe_2As_2 [15], with the closed blue circle denoting the momentum transfer of the 2-dimensional (1/2,1/2,0) antiferromagnetic correlations. (b) Phonon-roton dispersion relation in superfluid ^{4}He, with the closed blue circles denoting the Bragg points of the hexagonal closed-packed (HCP) phase of solid He [19]. (c) Correlations between the transition temperature T_c and the energy $\hbar\omega$ of the magnetic resonance mode observed in the superconducting state of the high-T_c cuprate systems [16, 21], (Ba,K)Fe_2As_2 [15], $CeCoIn_5$ [17], and $CeCu_2Si_2$ [18]. The closed square symbols denote the "spin-gap" energy obtained from the low-energy end of the hour-glass dispersion shape [21]. The star symbols represent the lambda-point superfluid transition temperature T_c and the roton energies in superfluid ^{4}He at ambient and applied pressure [19]. The right-vertical and top-horizontal axes for He, $CeCoIn_5$ and $CeCu_2Si_2$ are both scaled by a factor 60 with respect to the left and bottom axes for the other systems. The aspect ratio is preserved, however, for direct comparisons of the slope $T_c/\hbar\omega$ of all the different systems. Updated after ref. [20] and adopted from ref. [6].